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Title: Cosmic Ray Muon Tomography

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Intended for: background slides for IAEA visitors

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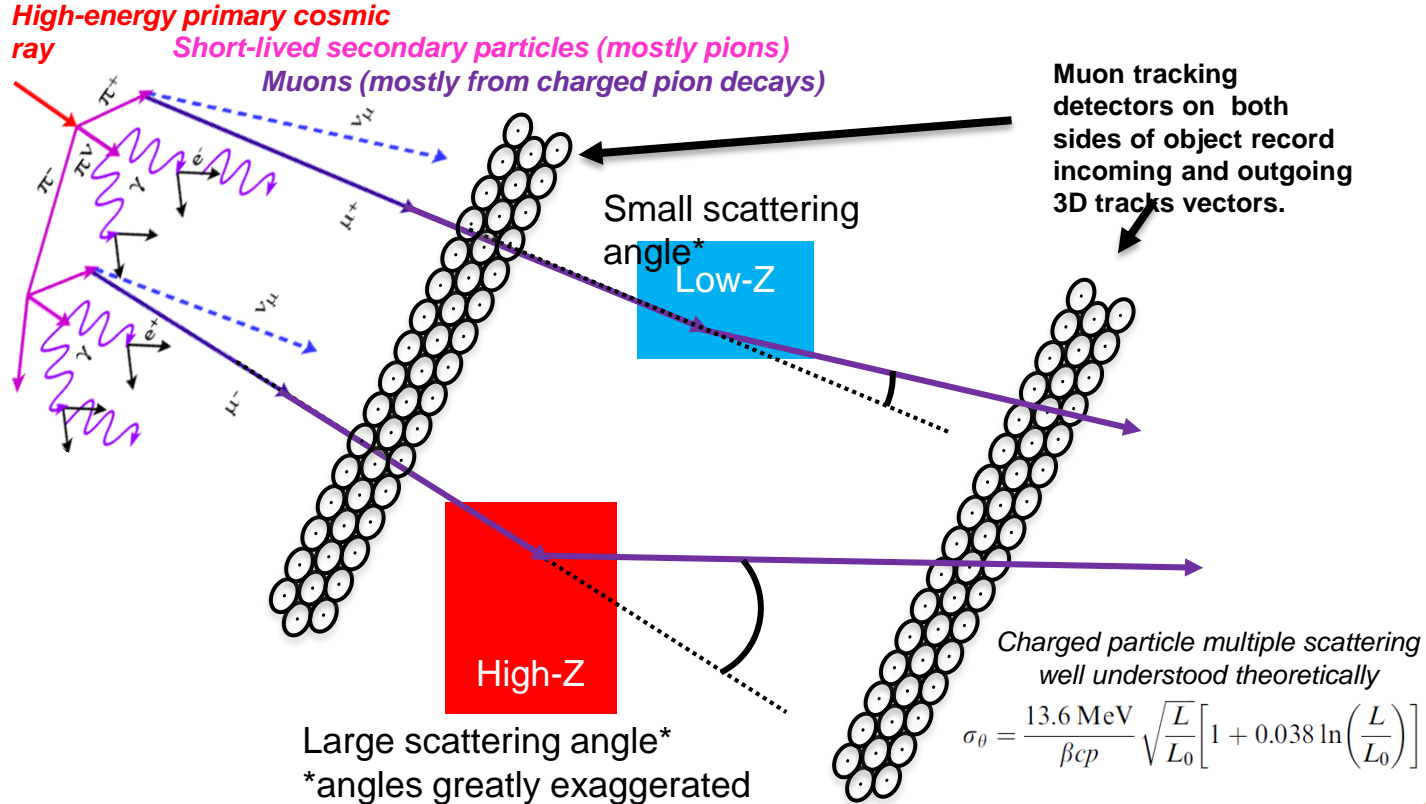
Cosmic Ray Muon Tomography

Matt Durham, *durham@lanl.gov*

P-25 Subatomic Physics

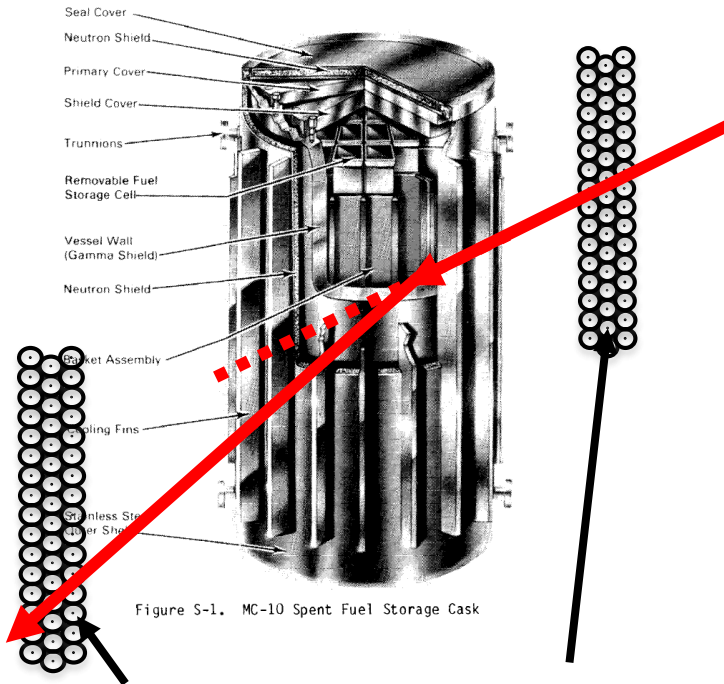
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Imaging with Muons



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Verification of Dry Cask Storage



Ideal candidate for muon radiography:

- Cosmic ray muons can penetrate meters of heavy shielding
- Muon scattering angle is dependent on Z of materials
- External probe that is insensitive to neutron/gamma backgrounds from neighboring casks

Layers of drift tubes record muon positions and trajectories before and after passing through cask

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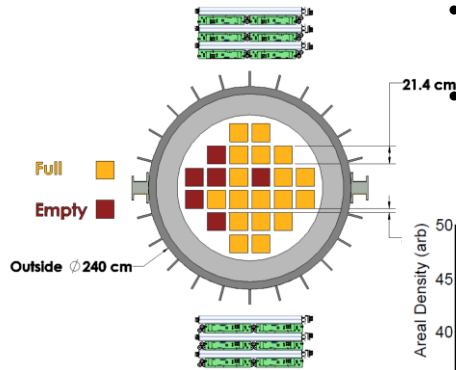
2015 Measurement at INL

Muon trackers in weatherproof enclosures. One side elevated to increase muon flux through both detectors (falls off as $\sim \cos^2 \Theta$).



Westinghouse MC-10 cask, count time ~ 200 hrs
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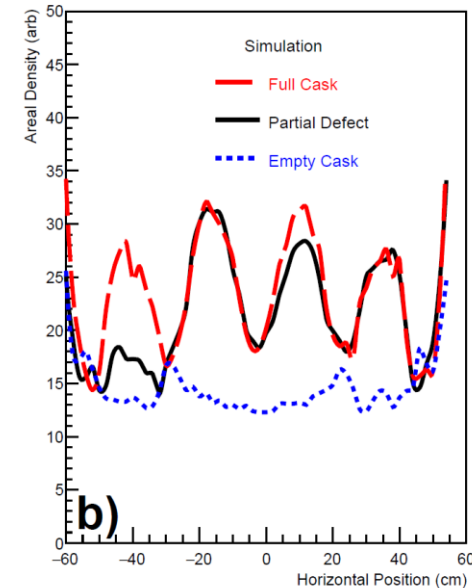
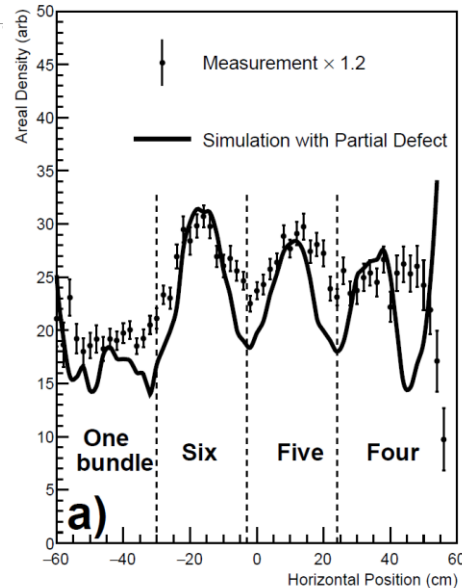
Imaging the Cask - Projection



- Clear difference across basket.

- The detector field-of-view encompassed rows in the fuel basket with one, six, five and four assemblies. Since these are ~uniform in the vertical direction, project density image data onto horizontal axis

Journal of Nuclear Materials Management **44** 3 (2016)

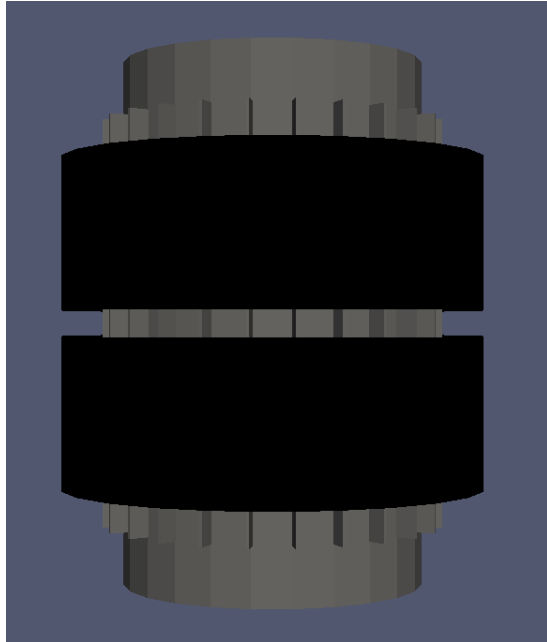


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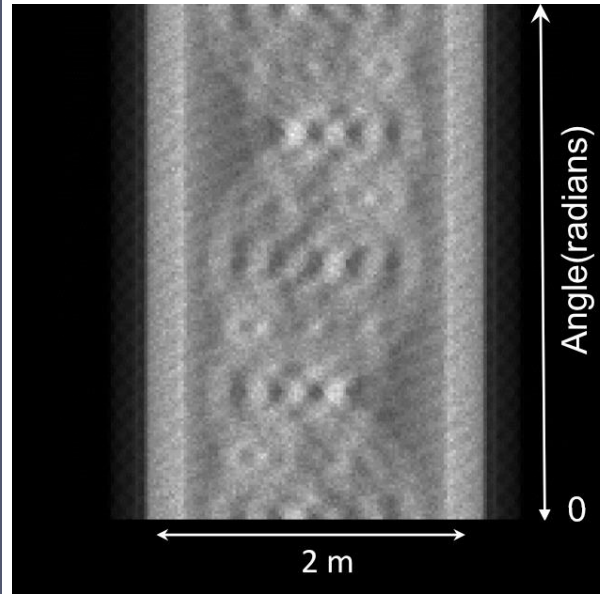
Ideal Detector Simulation

- Ring detectors around cask measure muon tracks from all azimuthal angles

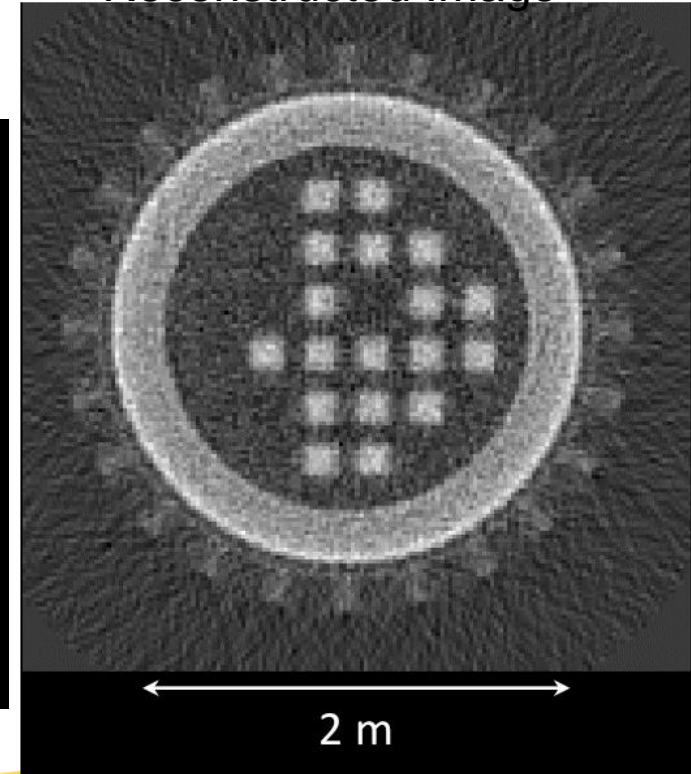
GEANT4 simulation



Sinogram of cask



Reconstructed Image

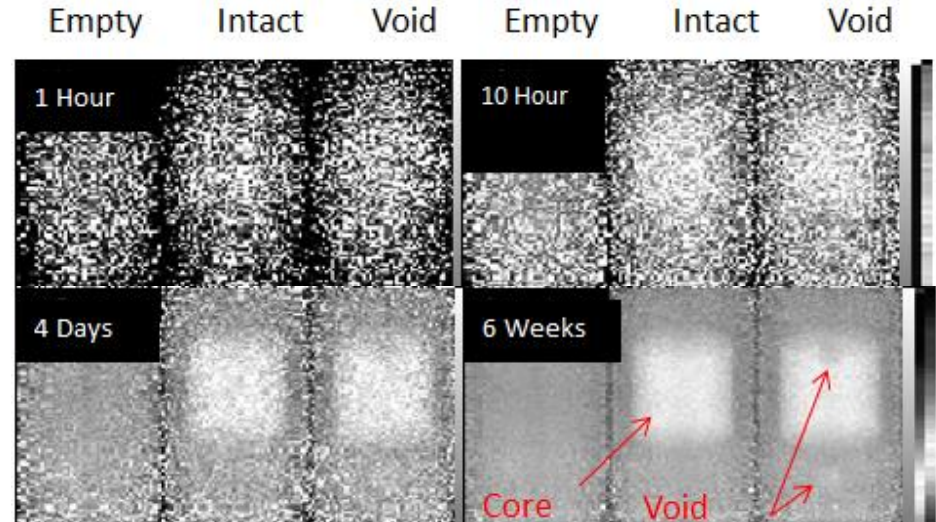
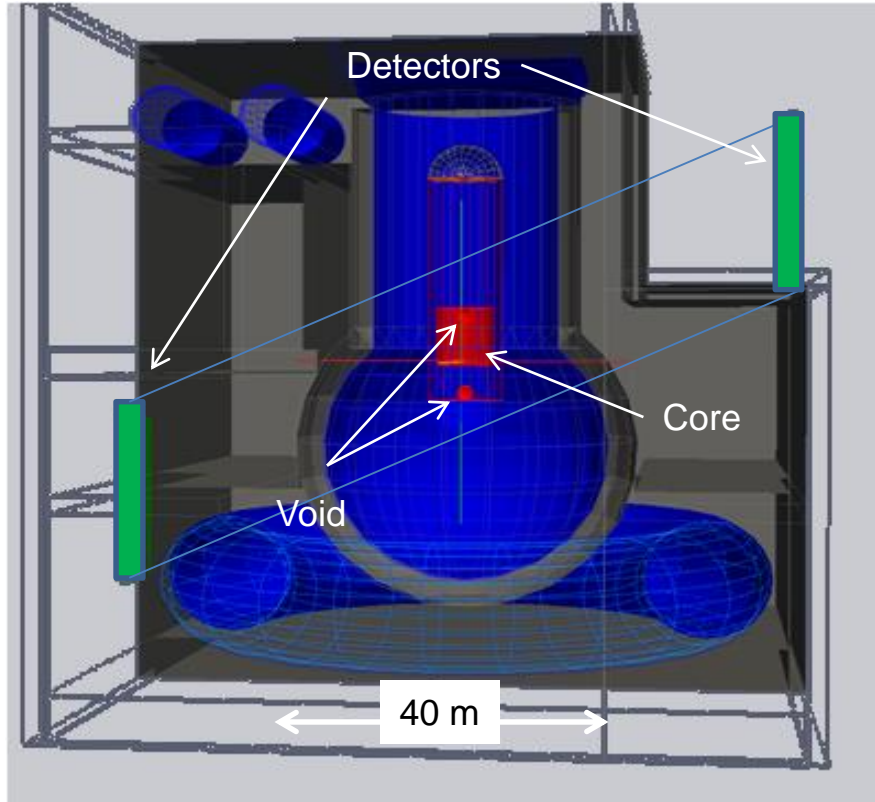


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Reactor Imaging with Cosmic Ray Muons

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Muon imaging at Fukushima - simulation



GEANT4 simulation. Results published in Physical Review Letters 109 152501 (2012).

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Toshiba Muon Tracker – 7x7m² modules



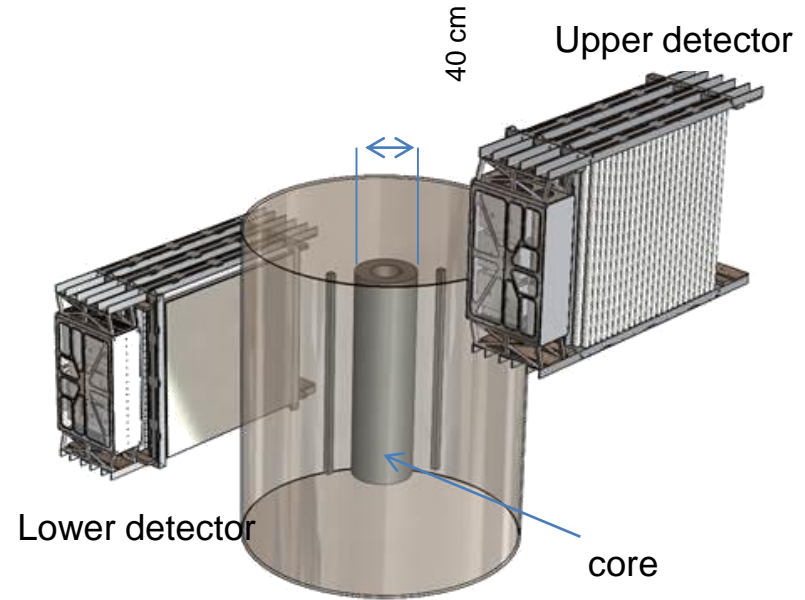
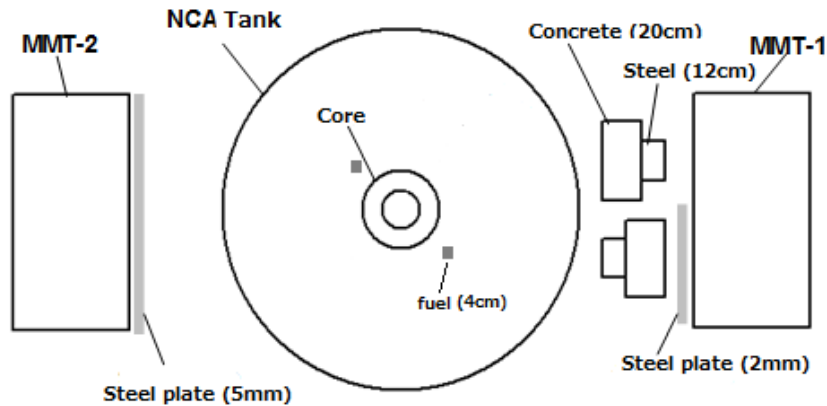
Full muon tracker assembled and tested at Toshiba in Yokohama, Japan.

Options for deployment at Fukushima Daiichi power plant are being explored.

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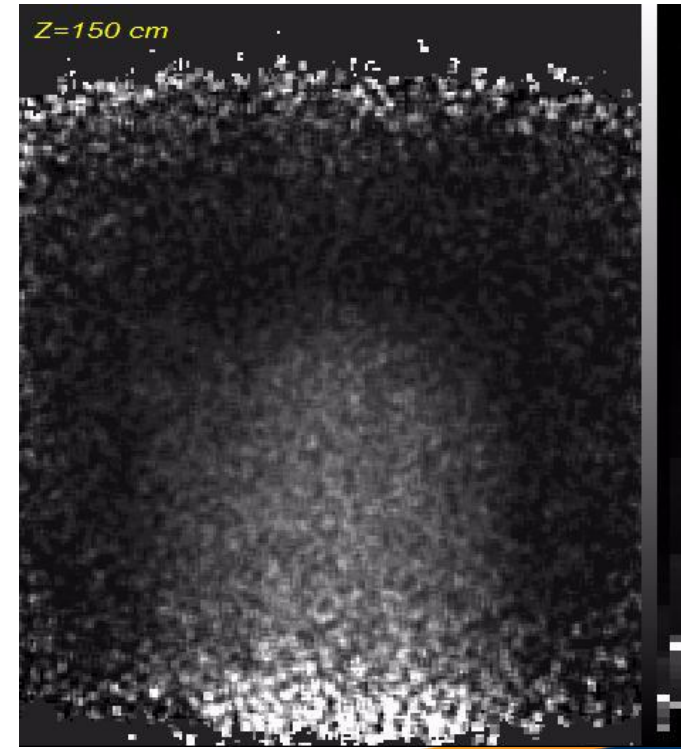
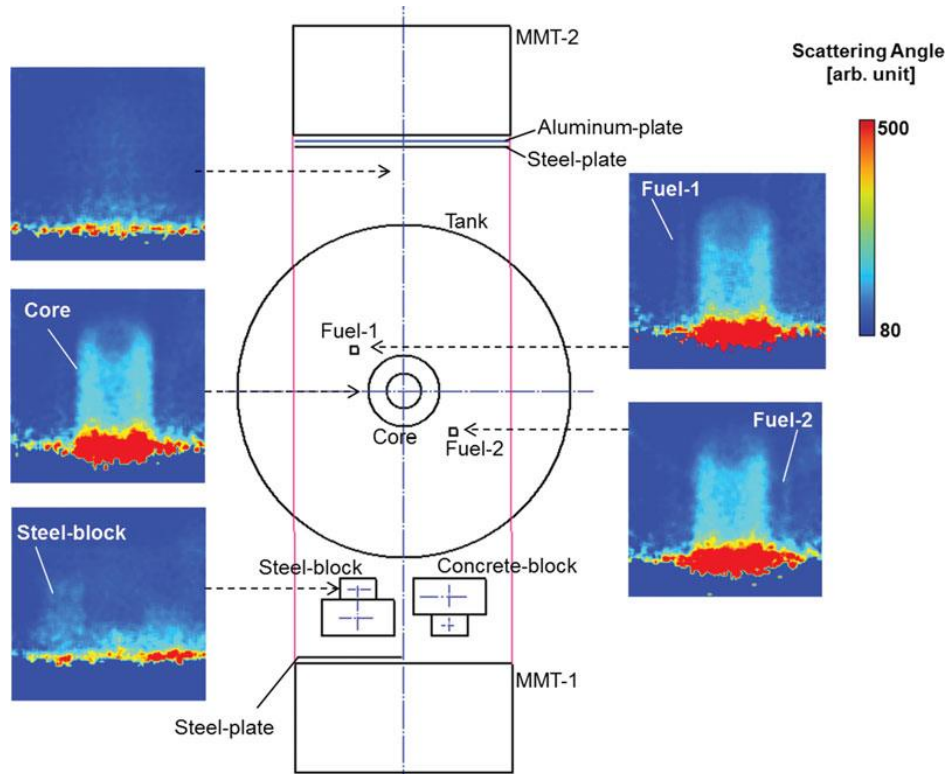
Proof of concept: Measurement at Toshiba CNA

-Effectively 1/10 scale demonstration of Fukushima reactor imaging



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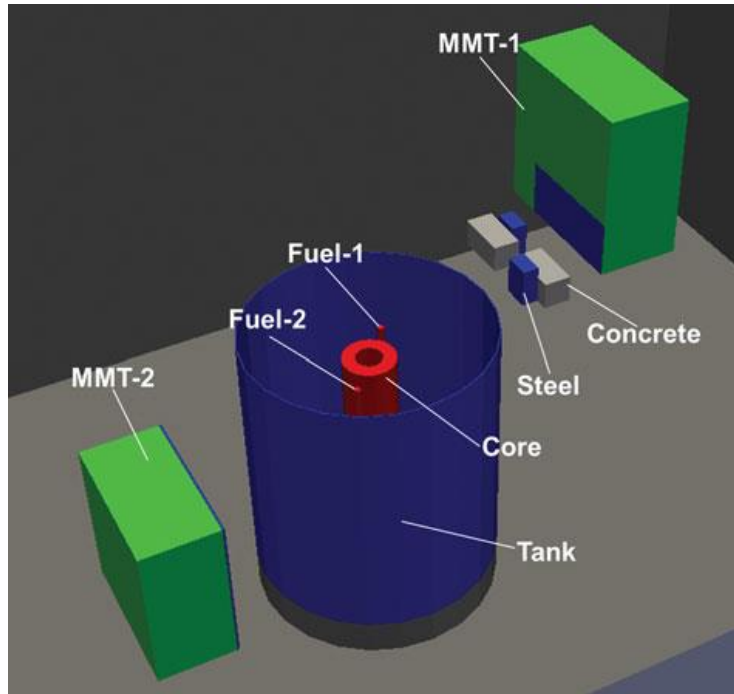
Toshiba CNA - Details



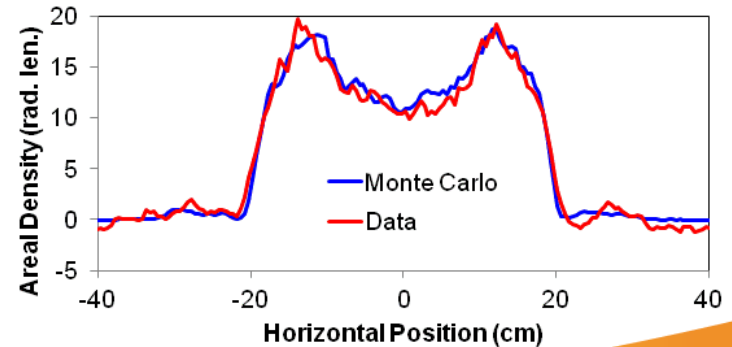
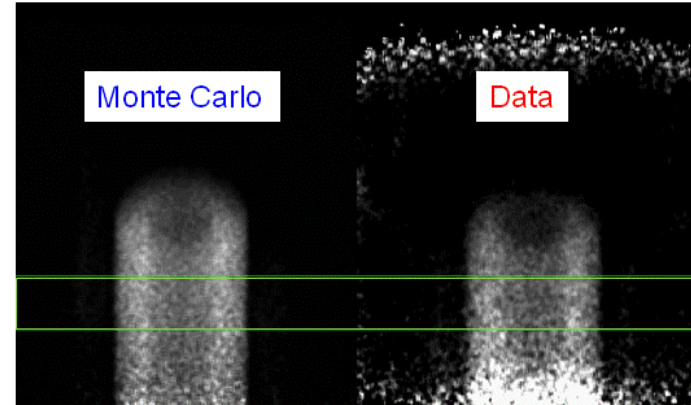
T. Sugita et al. Journal of Nuclear Science and Technology 51, 7-8 (2014)

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CNA Results – compare to simulation



GEANT4 Model of Reactor



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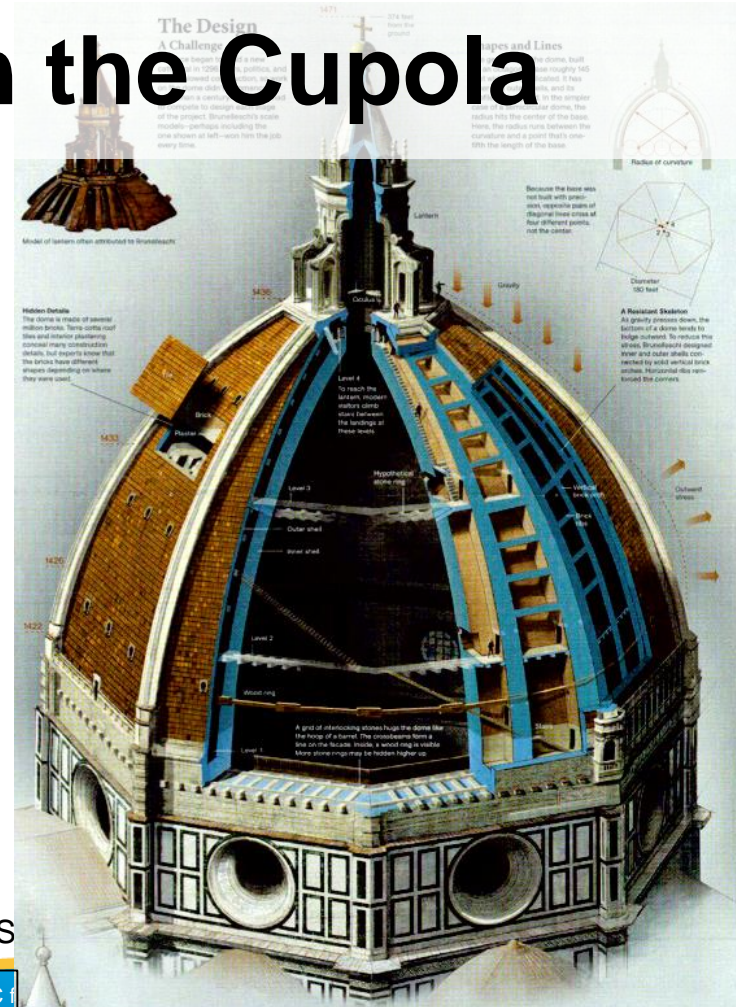
Imaging the santa Maria del Fiore Cupola in Florence, Italy



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Reinforcements in the Cupola

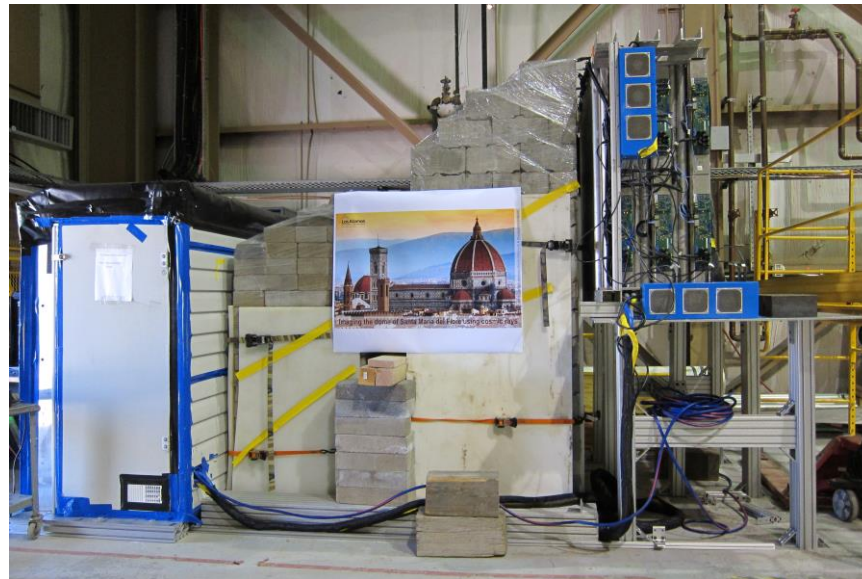
- Three pairs of *macigno* chains are believed to reinforce the Cupola.
 - Only the existence of the lowest pair have been proven.
- A wooden chain was also installed 7.75 m above the springing of the Cupola.
- Some scholars maintain that there are also iron chains inside the masonry.
 - Investigations with metal detectors have failed to yield conclusive evidence.
 - Thousands of Florentine pounds of iron (1 pound = 0.34 kg) were purchased during the construction of the dome.



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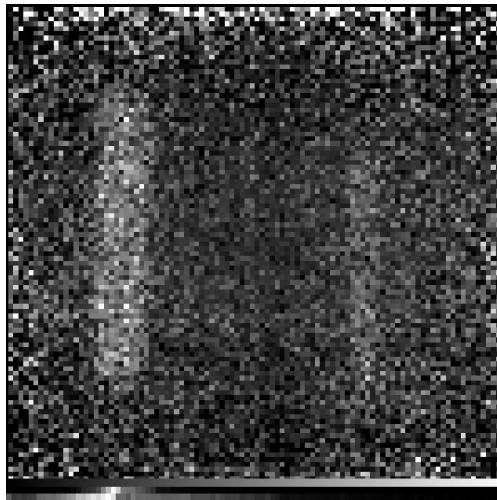
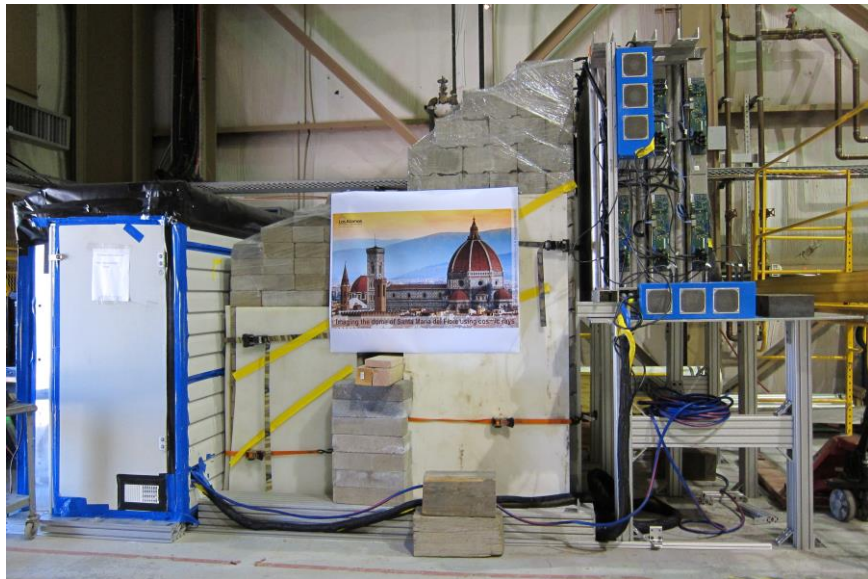
Demonstration measurement at LANL

- We deployed our two muon tracker modules on two opposite sides of the wall and took data for 35 days.

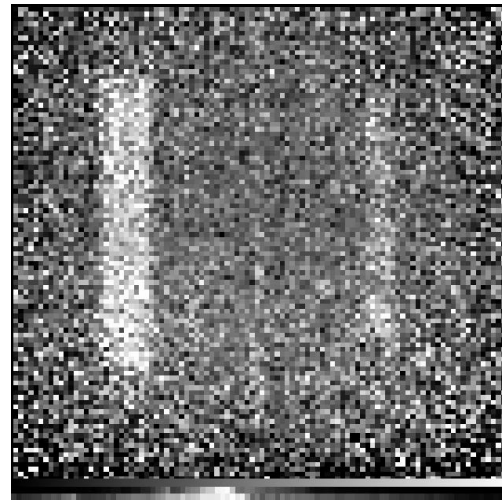


Cupola demonstration measurement

Steel bars imaged through 2m of concrete



Data



Simulation

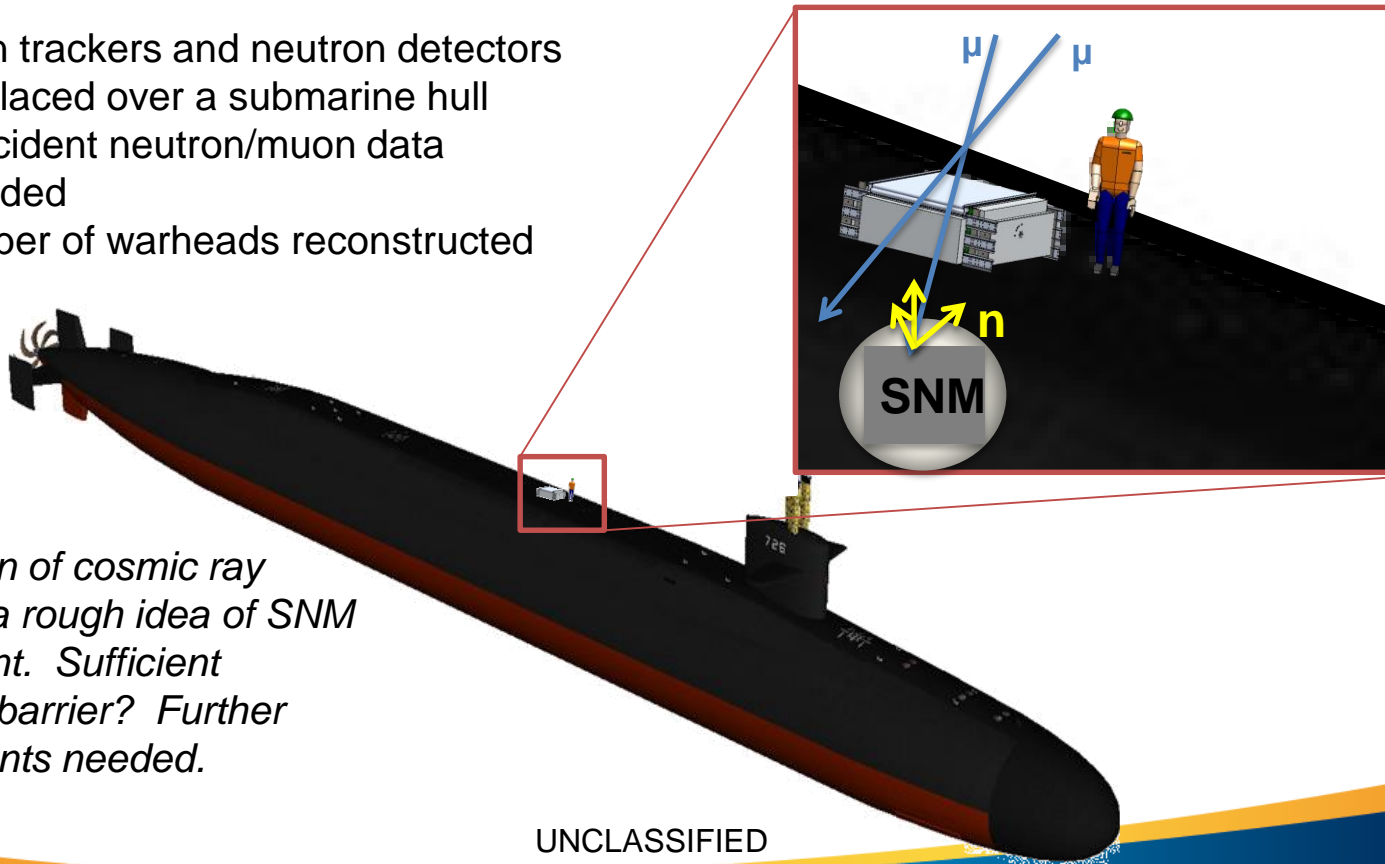
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Treaty Verification

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Application in Treaty Verification:

- Muon trackers and neutron detectors are placed over a submarine hull
- Coincident neutron/muon data recorded
- Number of warheads reconstructed

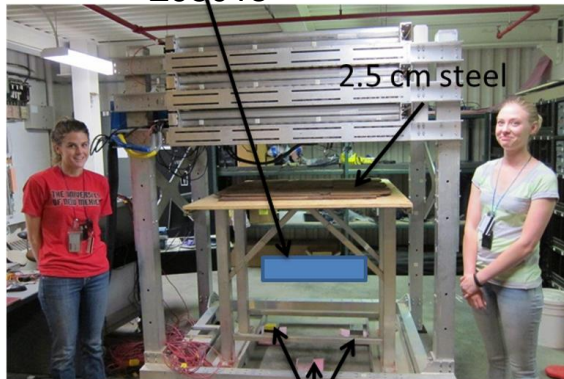


The direction of cosmic ray tracks give a rough idea of SNM spatial extent. Sufficient information barrier? Further measurements needed.

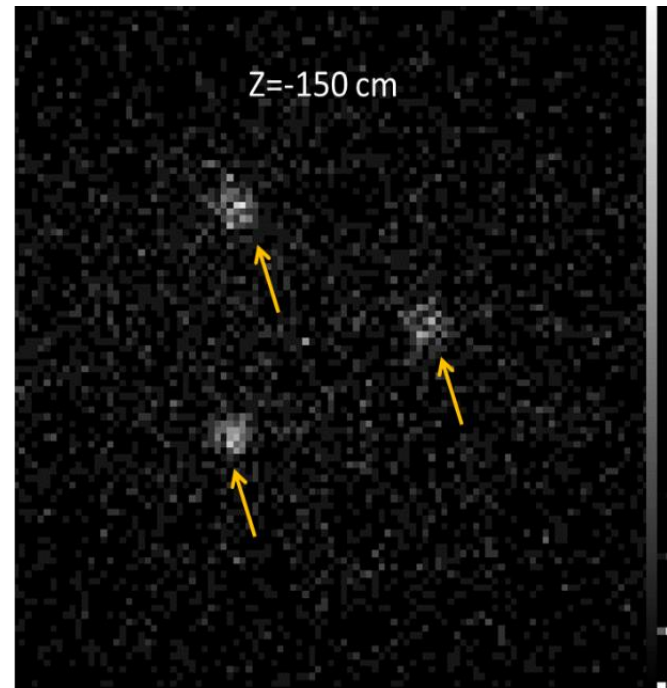
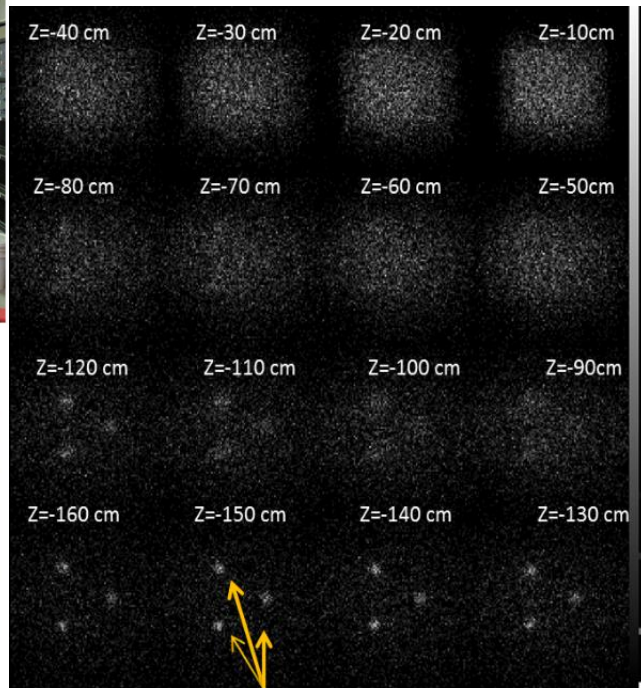
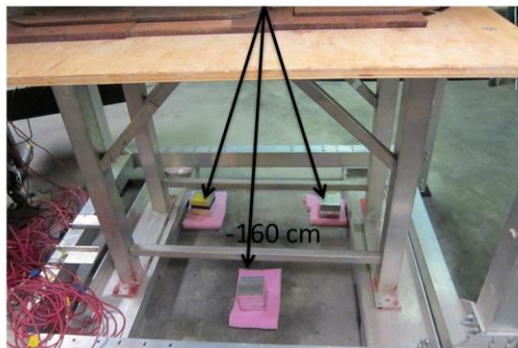
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Spatial discrimination of SNM

EJ301s



U cubes



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